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Liquid flow in tubes. V

Effects of lateral tube deflections on some turbulent transition quantities

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With 7 figures in the text

ABSTRACT

Previous investigations in this series of publications on the transition pattern for tube flow of liquids have shown that both structural properties of the liquids as well as microscopic mechanical properties of the tube walls may influence several characteristics of the appearance and development of turbulent slugs. The present observations further indicate that rather slight lateral tube deflections may influnece the transition pattern, causing the burst and development of turbulent slugs in primarily undisturbed laminar flow at higher Reynolds numbers, while simultaneously a distinct damping effect is noted on the rate of development of already existing turbulent streaks when compared with their rate of extension in straight tube flow. Furthermore, within the region of transition at lower Reynolds numbers, the damping effect may dominate over the self-preserving turbulence mechanism to such an extent that turbulent slugs developed in a straight part of the tube may be damped out completely in a following curved part of it.

The findings seem to complete observations on flow through helical tubes reported by C. M. White 1929 and G. I. Taylor 1929.

Introduction

In previous papers of this series (Lindgren 1959*c*; 1960) it was reported that both structural properties of the flowing liquids and tube dimensions as well as microscopic surface roughnesses may influence the transition pattern. Five extruded plexiglass tubes 4.94 m in length and with diameters of 3.82, 6.13, 9.80, 16.05 and 23.72 mm were used in those experiments. The three largest tubes were run in experiments not only with as "extruded" surfaces but also sand-blasted. However, the sand-blasted tube surfaces were clearly to be considered hydraulically smooth (see Lindgren 1960) in view of classical concepts of the turbulent boundary-layer theory.

The current report presents some experimental evidence that even a slight curvature of a tube may influence the initiation and development of turbulent slugs and streaks.

Experimental arrangement

The present experiments were run with the 9.80 ± 0.04 mm sand-blasted plexiglass tube in identically the same manner, using the same experimental equipment (see Figs. 1 and 2) and bentonite suspension as described in the previous paper of this series (Lindgren 1960, pp. 450–451).

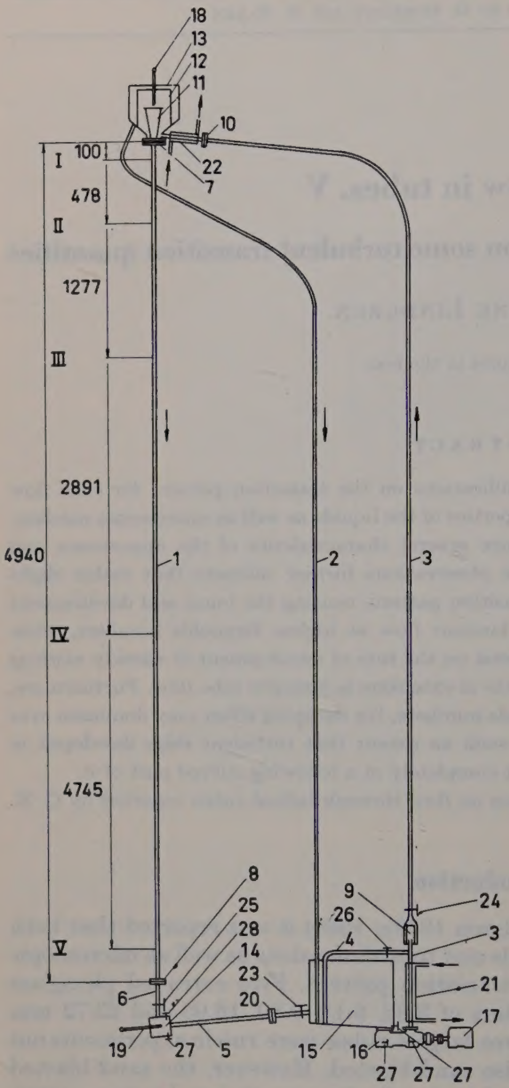

Fig. 1. Arrangement of the experimental flow apparatus

1. Experiment tube
2. Overflow returnpipe (PCV plastics)
3. Feeding pipe line (PVC plastics)
4. Short circuit plexiglass pipe
5. 2 measuring pipes
6. Joint hose (PCV plastics)
7. Inlet arrangement from the levelling tank to the experiment tube (see Fig. 2)
8. Coupling flanches
9. Glass wool sieve
10. Glass-fiber-fabric sieve
11. Outlet trumpet from the levelling tank
12. Levelling tank
13. Covering container
14. Calming tank
15. Supply container
16. Circulation pump
17. Electric motor

18, 19. Thermometers

20. 2 housings with measuring orifice plates

21, 22. Heat exchangers

23. 2 regulation cocks

24–26. Stop cocks

27. Tap cocks
28. Bleed cock

Observations on the appearance and propagation of turbulent slugs as dependent on certain lateral deflections of the tube

The results of the experiments with flow through the 9.80 mm straight tube are plotted in the diagram of Fig. 3*a*, which is identical with that of Fig. 5 in the foregoing paper (Lindgren 1960, p. 455).

Fig. 3*b* shows the corresponding plot for the tube having a slight S-bend of the measuring distance between Stns IV and V, as shown in Fig. 4.

We note from the smooth curves in Fig. 3*c*, extracted from the plots of Fig. 3*a* and *b*, that the double bend of the tube has caused a distinct increase of the relative

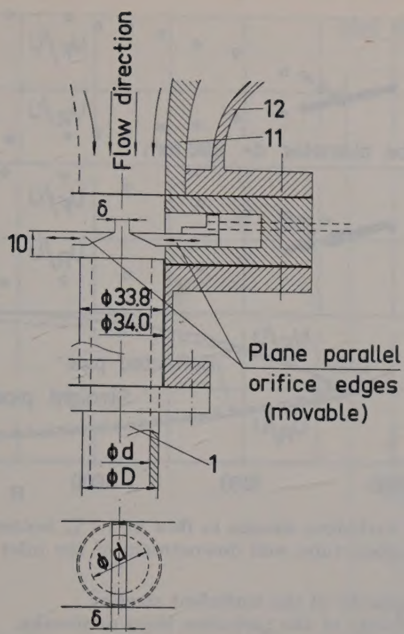

Fig. 2. Arrangement of the experiment tube inlet. 1, experiment tube; 11, outlet trumpet from the levelling tank; 12, levelling tank: d = inner tube diameter, D = outer tube diameter. During the present set of experiments the disturbance level of the inlet flow was varied by variation of the width, δ, of the slit between the orifice edges. (Above the coupling flange the outer diameter of the experiment tube is increased to 33.8 mm in order to avoid a "dead" liquid volume.)

velocity of the rear of the slugs, U_R/U (U_R = rear velocity of the turbulent slug, U = mean flow velocity), i.e. the plot for U_R/U versus the Reynolds number, R, is shifted towards higher U_R/U values for the flow through the curved tube ($R = Ud/\nu$; d = tube diameter; ν = kinematic viscosity).

On the other hand, above the critical Reynolds number $R_k \approx 2350$ we note the reverse effect, i.e. a decrease (shift toward lower values of the relative front velocity of the slugs, U_F/U, as caused by the lateral deflections of the tube. The two effects mentioned, together result in a distinct decrease of the relative expansion velocity, $(U_F - U_R)/U$, of the slugs.

Neither the transition Reynolds number $\underline{R}$ ($\underline{R} \approx 2000$) nor the critical Reynolds number R_k ($R_k \approx 2350$) appears to have been influenced by the tube deflections (for definitions of $\underline{R}$ and R_k see Lindgren 1960, p. 452). This state of affairs, however, must be seen in view of the fact that the initiation and development of the turbulent slugs, within the lower Reynolds numbers region, exclusively started in the straight part of the tube.

Another effect caused by the tube curvature was, that within the transition Reynolds numbers region $2000 < R < 2150$, occasionally a slug recorded at Stn IV (and upstream of it) did not arrive at Stn V, but faded away before reaching it, or there appeared only the last remnants of turbulent slugs, which would probably have faded away completely had the tube been long enough. The two parts of the same oscillogram of Fig. 5 recorded at a Reynolds number of $R \approx 2040$ show one slug which has disappeared after passing Stn IV but before arriving at Stn V; then, later,

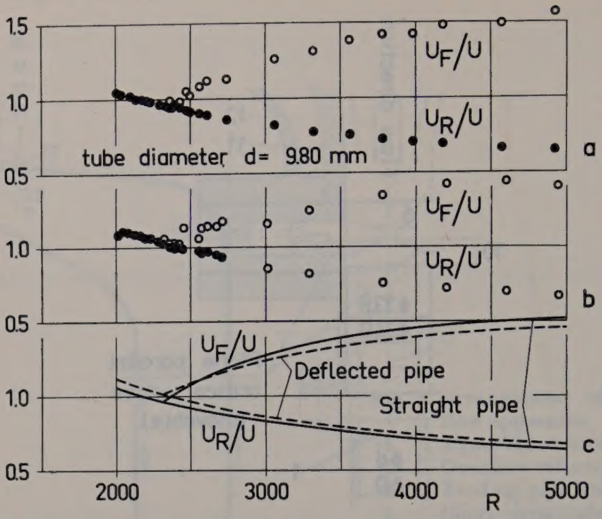

Fig. 3. Characteristic data of turbulent streaks in flow of 1.7‰ bentonite sol through a 9.80 mm sand-blasted cylindrical plexiglass tube well downstream of the inlet flow region (between Stns IV and V in Fig. 1).

U_F/U = relative front velocity of the turbulent streaks.
U_R/U = relative rear velocity of the turbulent slugs or streaks.
U = mean flow velocity.
$R = Ud/\nu$ = Reynolds number, where ν = the kinematic viscosity of the flowing liquid.

The roughness elements of the sandblasted tube surface are of an order of magnitude smaller than necessary in order to classify the surface as hydraulically smooth. A surface micrograph of it is shown in Fig. 3*B*, *c* of the previous paper in this series (Lindgren 1960, p. 453).

The plot of diagram *a* contains the experimental data obtained when the tube was straight, while diagram *b* shows the same plot for flows through the tube when its measuring distance (Stn IV to Stn V) possessed lateral deflections as shown in Fig. 4. on p. 537). (Diagram *a* is identical with the plot given in Fig. 4 of the previous paper in this series (Lindgren 1960, p. 454).)

The smoothed curves of the plots of diagrams *a* and *b* are drawn in diagram *c* for the purpose of comparison. We note that the tube deflections have caused a decrease of U_F/U when $R \gtrsim R_k$ and an increase of U_R/U. The $\underline{R}$ and R_k values appear not to be influenced by the tube curvature so far as these experiments are concerned.

another slug that is self-preserving all along the tube, downstream of its location of birth. This is a good demonstration of how uncertain the conditions for self-preservation of turbulence may be, since the measurable flow conditions are identical for the two slugs recorded, following on each other within a time interval of 2 minutes. The oscillogram records of Figs. 6 and 7 show similar developments for turbulent slugs or streaks. It is interesting to note that in different parts of each oscillogram transition developments appear which seem to be reverse to each other.

In the oscillogram of Fig. 6, where $R \approx 4600$, we note three indications of turbulent bursts (*a*, *b* and *c*) at Stn II. These bursts, however, did not develop into turbulent streaks, although their remnants still are observable at Stn III. However, two other bursts (*A* and *B*) at Stn II have developed into turbulent streaks already at Stn III with further expansion downstream. About 15 seconds later there follows another burst (*C*) at Stn II which develops into a turbulent streak of considerable length at Stn V. Here we note that the streak is preceded by a turbulent slug which was not recorded at any of the Stns upstream. Evidently this slug has nothing to do with the

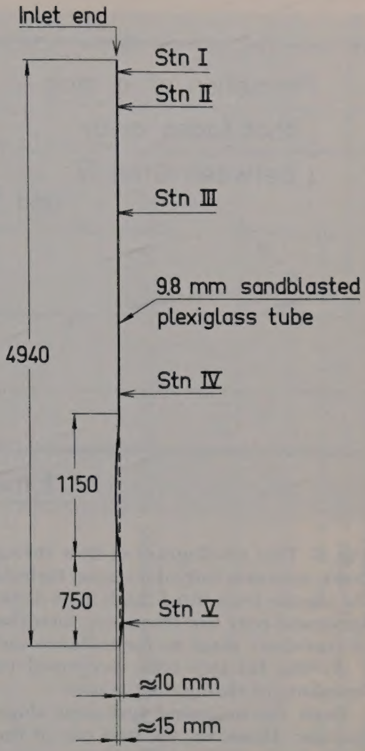

Fig. 4. Schematic drawing of the experiment tube with its bent measuring distance (Stns IV to V).

following streak, but has burst into existence and (by judging its frequency pattern) has begun to develop into a self-preserving expanding turbulent streak.

In the oscillogram of Fig. 7 we note the burst and development of a turbulent streak within the "fully developed" flow region between Stns IV and V at a Reynolds number of $R \approx 4940$. This time the new slug follows after the passage of a streak which has burst into existence within the inlet flow region and which is caused by the breakdown of inlet disturbances (indicated by A in the oscillogram). The streak formed in the curved part of the flow between Stns IV and V evidently has nothing to do with the preceding "regular" turbulent streak. Neither does it seem to be connected with the breakdown within the inlet flow region (indicated by *b* in the oscillogram), the eddies of which seem to be completely damped out before reaching Stn IV, according to the diagram. This interpretation is supported by the fact that no breakdown whatsoever of inlet disturbances can be traced in the same oscillogram to forego the turbulent streak which has been formed between Stns IV and V about 5 minutes later without being in the neighbourhood of a more "conventional" streak emanating from the inlet flow region.

The observations reported above have been noted for flows through the tube both before and after sand-blasting. They have also been noted for flows through the smaller, not sand-blasted, tubes when these have been deflected. However, the formation of a turbulent slug downstream of Stn III has never been observed up to the maximum Reynolds numbers applied in the experiments ($R \approx 10{,}000$) as long as the tubes have been visually straight.

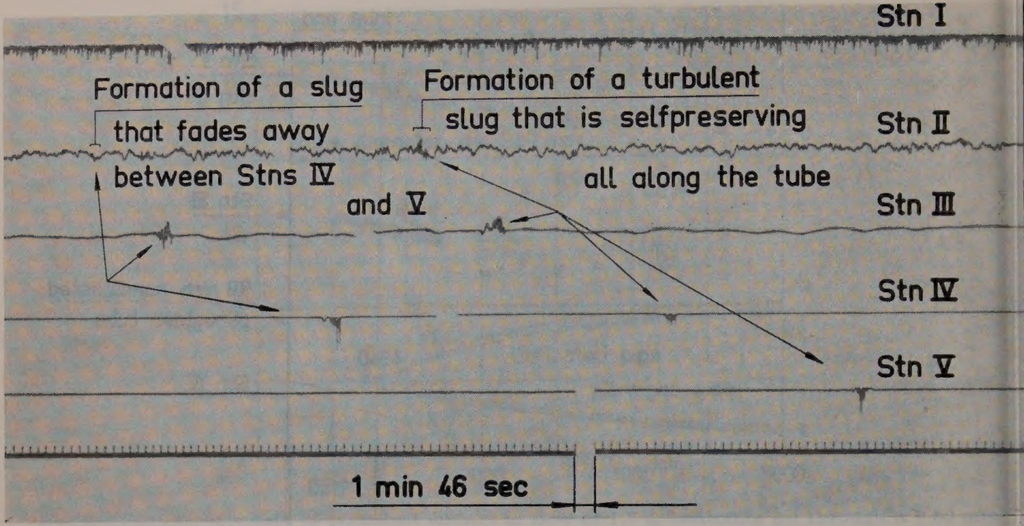

Fig. 5. This oscillogram of flow through the bent experiment tube, at a Reynolds number of $R \approx 2040$, indicates fully developed turbulent flow at the tube inlet according to the trace representing the signals from Stn I (high inlet disturbance level). At Stn II most of the small eddies have faded away and only low frequency disturbances remain among which we note the burst and formation of turbulent slugs as for instance indicated by the arrows.

At Stn III two fully developed turbulent slugs appear together with the last slow moving remnants of fading inlet eddies.

Both the indicated turbulent slugs exist also at Stn IV, where the flow otherwise is purely laminar. However, the first one of these slugs disappears somewhere between the Stns IV and V while the second one is self-preserving all along the tube.

The experiments clearly indicate that the noted disappearance of slugs between Stns IV and V is due to the lateral deflections of the tube within this measuring distance.

Each scale division in the lowest trace of the oscillogram correponds to a time interval of 3/10 of a second.

The fading away of initially formed turbulent spots or slugs within the inlet flow region in straight tubes as demonstrated for instance by the oscillogram Fig. 6 (see also Lindgren 1957, pp. 33–36; 145–148) is another phenomenon which so far has been more or less regularly observed in all experimental studies hitherto performed. However, some previous reports of turbulent slugs fading away rather far downstream perhaps could be interpreted in terms of lateral tube deflections (Lindgren 1957, p. 136), although efforts always have been made to avoid such deflections. In each case, however, it should be possible to decide whether the observations might have been influenced in this respect or not, and certainly it should not make any of the observations reported qualitatively invalid.

Conditions for asymmetric flow effects

In the present and similar experiments flow asymmetries may easily be checked by observing the location of the dark flow core stripe indicating zero shear stress. In this manner it may be concluded from the present experiments that moderate asymmetries of the velocity profile do not seem to influence the characteristics of the various

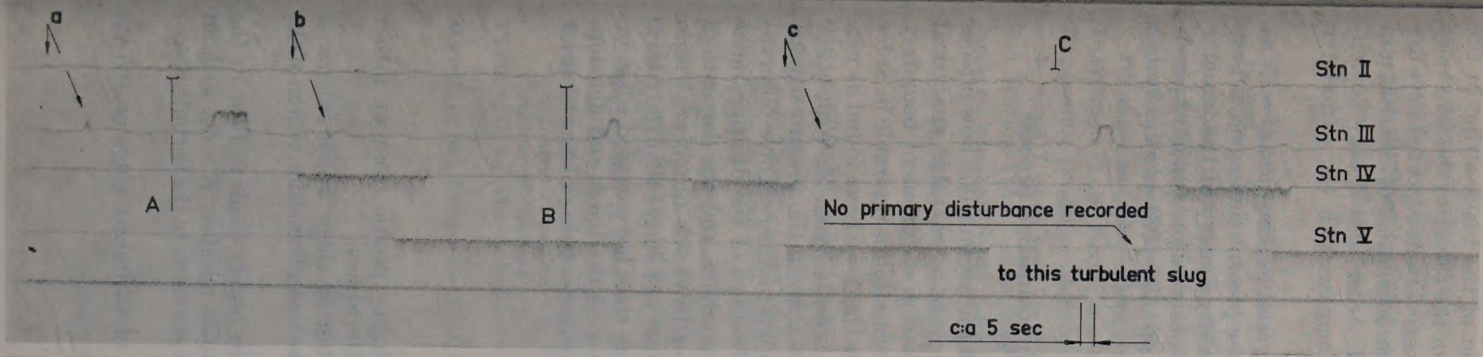

Fig. 6. Oscillogram record of similar flow to that of Fig. 5, but with a low disturbance level at the tube inlet and a Reynolds number of $R \approx 4600$.

The arrows *a*, *b* and *c* indicate the bursts of turbulent slugs at Stn II, which still exist at Stn III but fade away before reaching Stn IV. The indi cations *A*, *B* and *C* in turn show similar bursts at the same location (Stn II), these bursts, however, develop into expanding self-preserving turbulent streaks.

Finally, we also note the formation of a turbulent slug between Stns IV and V as due to the tube curvature, without any primary disturbance belonging to the slug being recorded upstream of it.

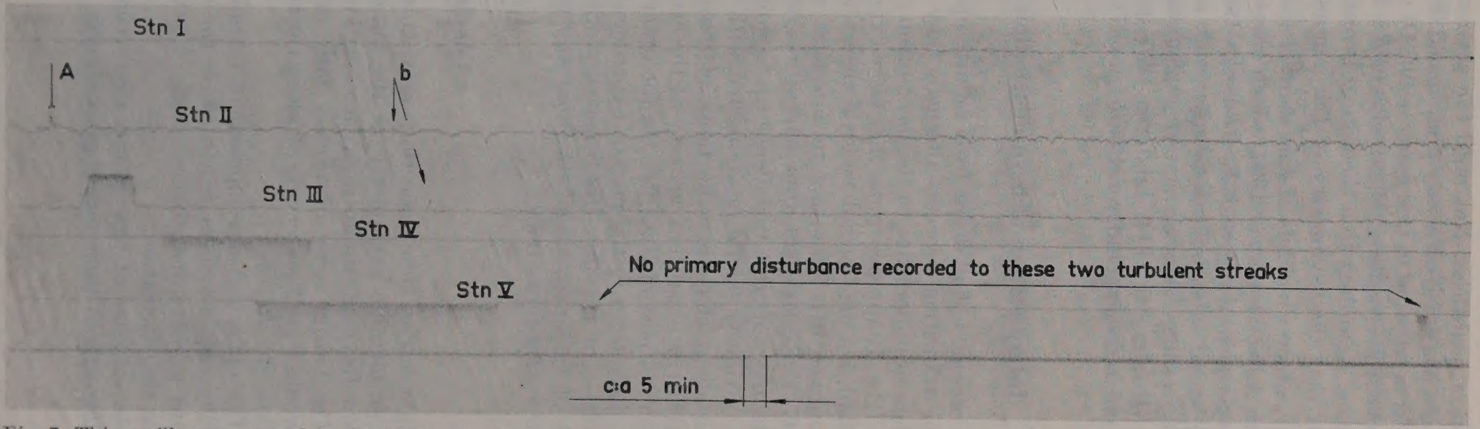

Fig. 7. This oscillogram record is obtained under the same conditions as that of Fig 6, but at a Reynolds number of $R \approx 4900$.

Also here we note a burst (*A*) at Stn II which develops into a self-preserving turbulent streak and another one (*b*) which fades away before reaching Stn IV. On the other hand, it seems as if this fading disturbance could have been the cause for the formation of the streak which follows after the first one and which seems to have been formed in the curved part of the tube (downstream of Stn IV) without any primary disturbance to it being observed at Stn IV.

However, most likely, disturbance *b* has nothing to do with the latter turbulent streak, just as no primary disturbance whatsoever can be connected to the turbulent streak formed between Stns IV and V about 5 minutes later.

transition quantities. Not until the asymmetric location of the black stripe in the flow core has received a very pronounced dislocation from the centre of the flow may the effects reported in this paper occur. Of course, the observations reported here are limited to a Reynolds number region of $R \lesssim 5000$ in flow through tubes of about 10 mm diameter. According to a theoretical investigation by M. Adler 1934 it may be concluded that the asymmetry of the laminar flow will increase with the parameter $R\sqrt{d/r}$, where r = radius of curvature of the tube.

Both Adler's report of 1934, which covers both theory and expriments, as well as the experimental report of E. Reshotko 1958, support the present findings; i.e. that slight lateral tube deflections may cause a considerable asymmetry of the laminar velocity profile. Thus we have an explanation for several observations reported previously (Kohlrausch 1914; Lindgren 1957, p. 37; 1959*b*, pp. 506–508) as already has been pointed out (Lindgren 1959*b*, p. 507).

Interpretation of asymmetric flow effects on the transition process

At present I shall desist from an attempt to interpret the asymmetric flow effects on the transition process, although they certainly provide a tractable analytical problem of importance to the mechanism of self-preservation of turbulent boundary layer flow. It appears to me that more experimental information is desirable in order to establish a solid boundary-layer theory which I do not think we have found as yet.

However, it is important to note that, according to reports by C. M. White 1929 and G. I. Taylor 1929, tube curvatures of higher grade than in the present experiments may suppress turbulence up to quite high Reynolds numbers. Those observations obviously should be connected with the present findings of the disappearance of turbulent slugs in tube flows of lower Reynolds numbers; and the decrease of the relative expansion velocity of the streaks at higher Reynolds numbers; within the curved part of the tube. On the other hand, we must not forget that the lateral tube deflections in the present experiments at the same time have caused some instabilities of the flow (the velocity profile?) thus initiating the burst and development of turbulent streaks without any primary disturbances being observed prior to these slug formations.

Conclusions

Slight lateral tube deflections may cause:

(*a*) Considerable asymmetry of the laminar flow velocity profile even at rather low Reynolds numbers (a fact long known in the literature).

(*b*) The fading away of already fully developed turbulent slugs which otherwise would be self-preserving all along the tube within the lower transition region of the flow $\underline{R} \lesssim R \lesssim R_k$.

(*c*) The burst and development of turbulent streaks in purely laminar flow in the Reynolds numbers region above the critical Reynolds number, $R > R_k$, without any primary disturbances being observed upstream previous to the turbulent spot or slug formation.

(*d*) An increase of the relative rear velocity, U_R/U, of turbulent slugs or streaks throughout their region of existence.

(*e*) A decrease of the relative front velocity, U_F/U, of turbulent streaks in Reynolds number regions $R \gtrsim R_k$.

(*f*) The conclusions noted under *b*, *d* and *e* here may represent various phases of the same phenomenon.

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As usual I have had the advantage of having my paper revised by Professors Sune Berndt and Hilding Faxén, both presenting important points of view. Especially Professor Berndt, however, has contributed much to the final version of the manuscript.

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